Studying Muons and Atmospheric Neutrinos in SNO

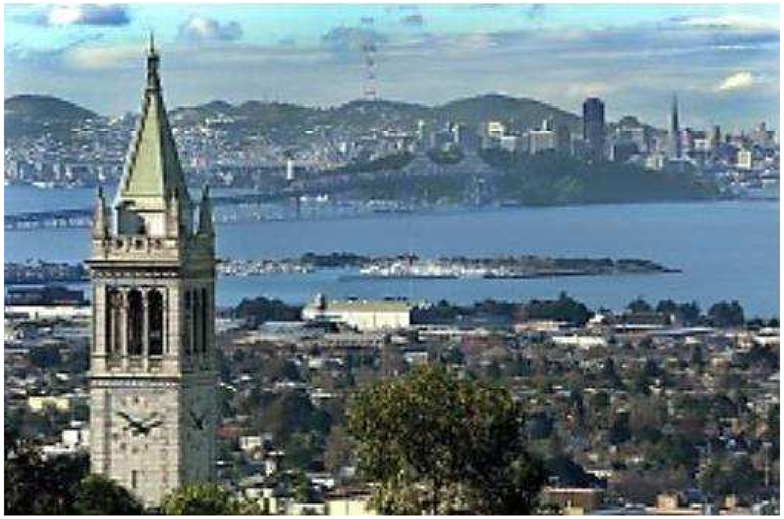
neutrino.lbl.gov/∼snoman/currat/talks/

Charles Currat
LBNL

October 11, 2004
NSD All Staff meeting

- Introduction
- SNO in a nutshell
- Atmospheric neutrinos
- Muon tracker

About me

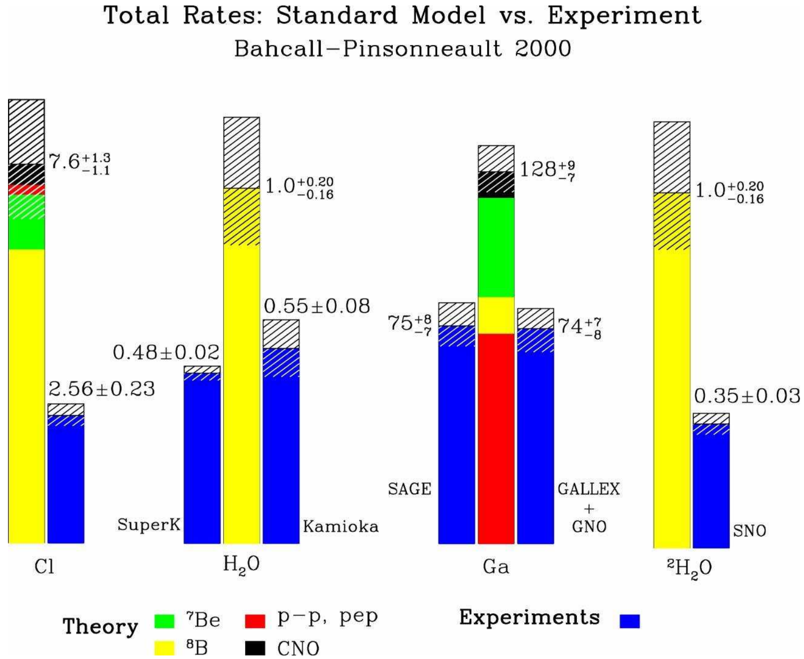


- Native from Switzerland
- Graduated in physics from Swiss Federal Institute of Technology at Lausanne (ETH)
- PhD in HEP at U of Lausanne and CERN
  - NOMaD, accelerator based neutrino experiment (90s: short baseline)
  - RD46, detector technology: liquid scintillator filled micro-capillaries as vertex detector
  - LHCb, B-physics spectrometer at LHC
- Postdoc visitor in the CDF group at LBNL (L. Galtieri, PD)
- Postdoc fellow on SNO at LBNL (K. Lesko, NSD)

The SNO group at LBNL

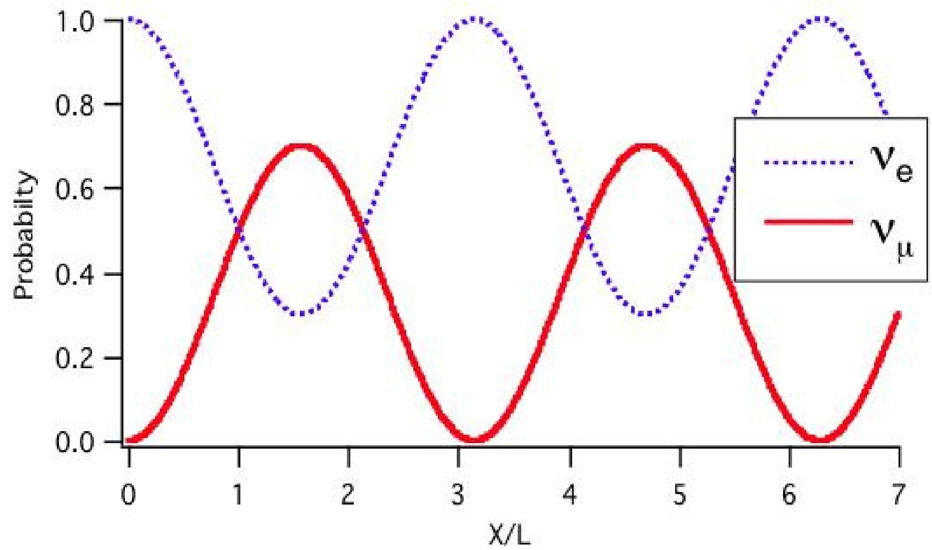
The solar ν problem in a nutshell

Prior to SNO, 5 experiments, with 3 different target materials over 35 years have measured a deficiency of solar neutrinos.



- SNO was first proposed in mid-1980s
- Realized that using heavy water instead of water can allow for the detection of all active neutrino flavors (late Herb Chen, UCI)
- SNO was designed to provide a "smoking gun" for oscillations by measuring whether or not total solar neutrino flux is greater than the electron neutrino flux

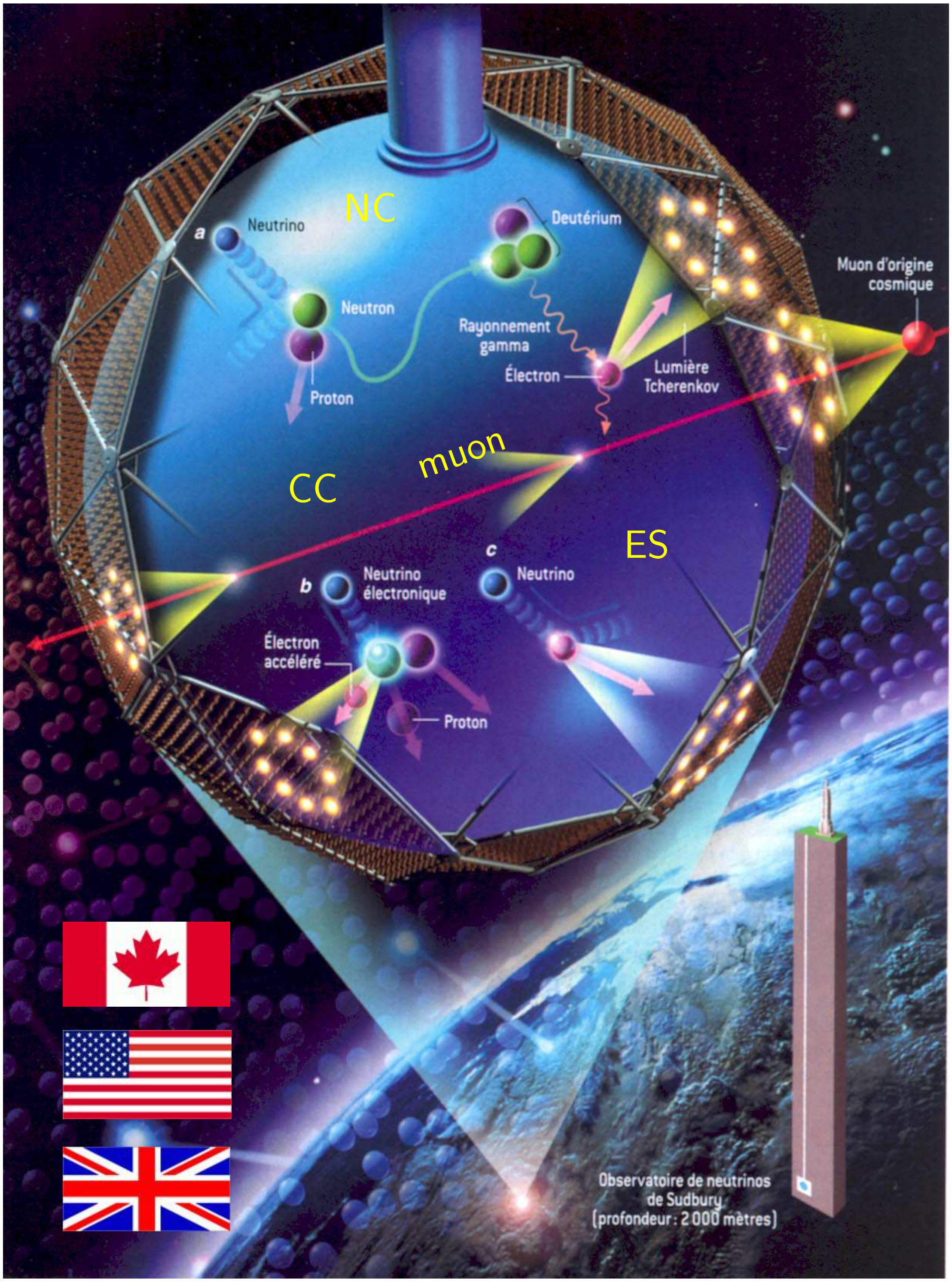
If: ν have mass, masses are not equal, mass states are different from the flavor states ⇨ neutrinos can change flavor: $|\nu_\alpha\rangle = U_{\text{mix}}\,|\nu_i\rangle$



Similar to mixing seen in quarks. Probability of a ν with momentum p remaining in given flavor state ℓ as a function of distance traveled is governed by 2 parameters θ and Δm^2

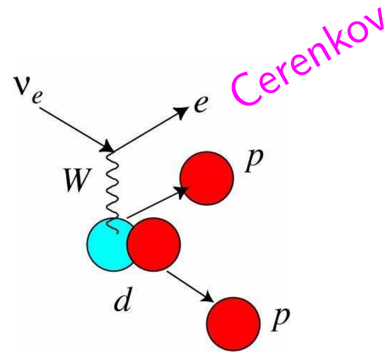
$$P(\ell \to \ell, x) = 1 - \sin^2 2\theta \times \sin^2(1.27 \cdot \Delta m^2 \cdot L[\text{km}]/E[\text{GeV}])$$

SNO: a neutral current detector



NC detector: key physics signatures

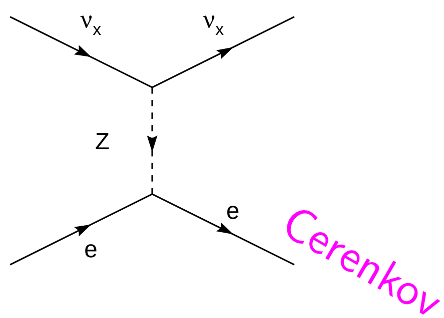
CC



$\nu_e + d \to p + p + e^-$

- gives ν_e energy spectrum well
- weak direction sensitivity $\propto 1 - \frac{1}{3}\cos\theta$

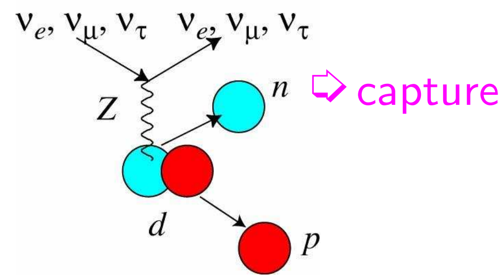
ES



$\nu_x + e^- \to \nu_x + e^-$

- low statistics
- mainly sensitive to ν_e, some sensitivity to ν_μ and ν_τ
- strong direction sensitivity

NC



$\nu_x + d \to p + n + \nu_x$

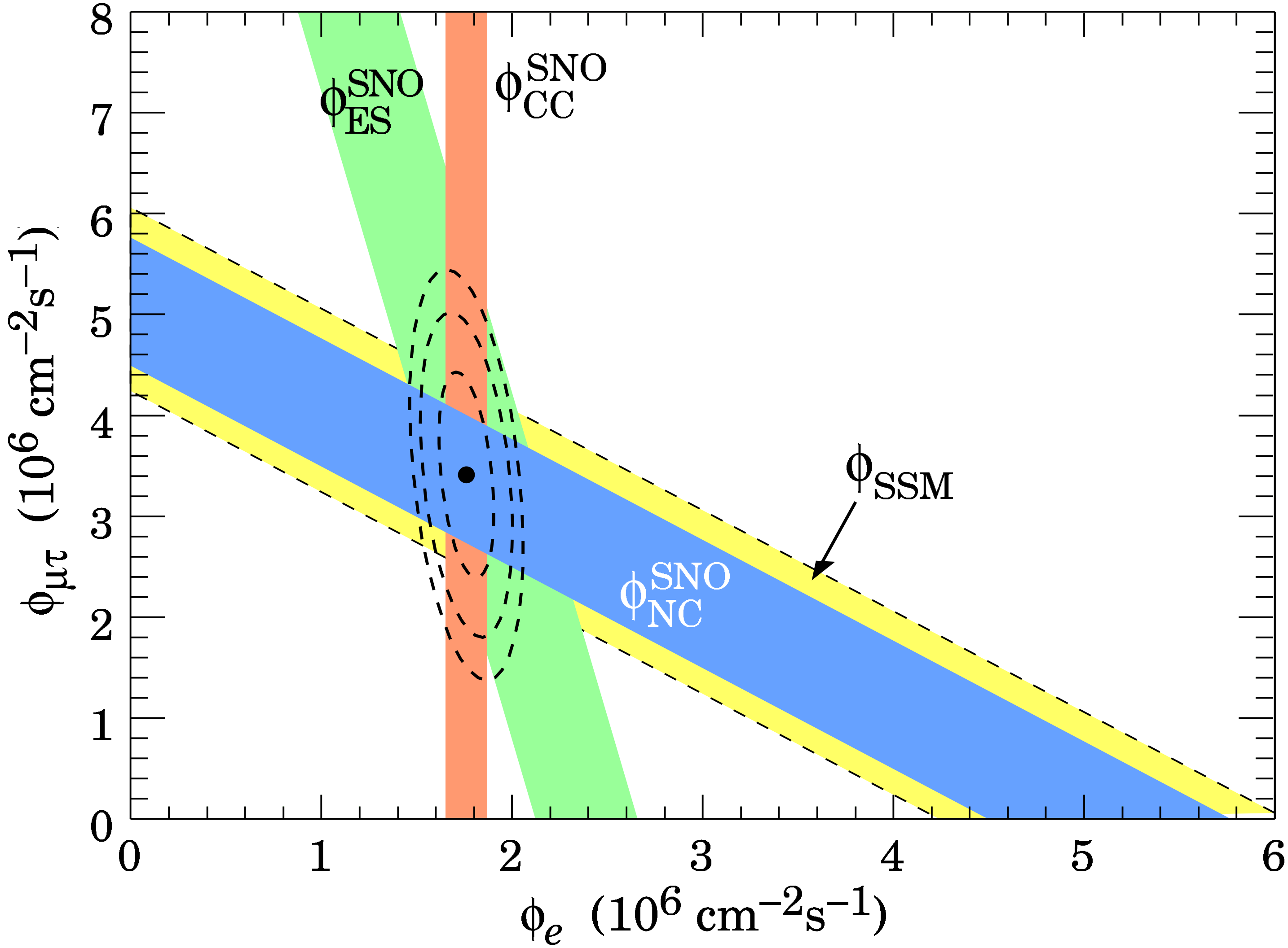
- measures total ^{8}B ν_x flux from the sun
- equal cross section for all ν types

$$\frac{\Phi_{\text{CC}}}{\Phi_{\text{NC}}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

$$\frac{\Phi_{\text{CC}}}{\Phi_{\text{ES}}} = \frac{\nu_e}{\nu_e + 0.154 \cdot (\nu_\mu + \nu_\tau)}$$

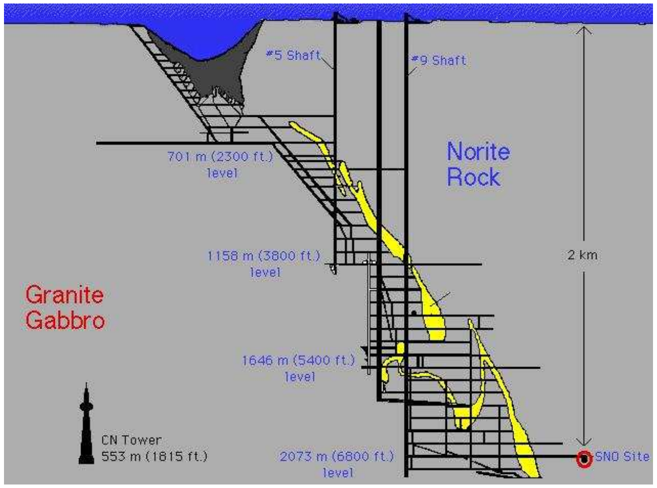
Solar fluxes in SNO

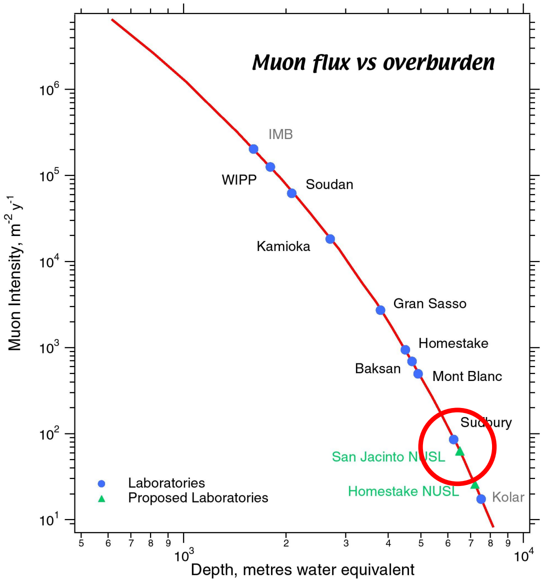
Fluxes of ^{8}B solar neutrinos deduced from SNO results for pure D_2O



Geography

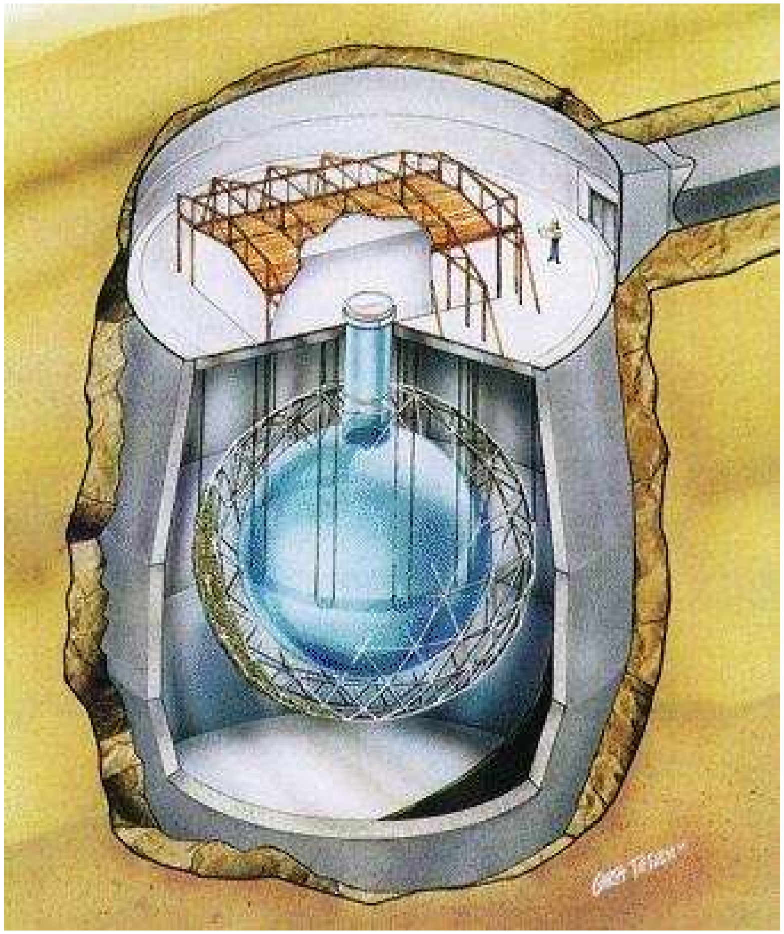
SNO detector located at the INCO Ltd Creighton Mine, Sudbury ON, Canada
➪ deepest mine in activity ⊕ heavy water on loan from CAN government

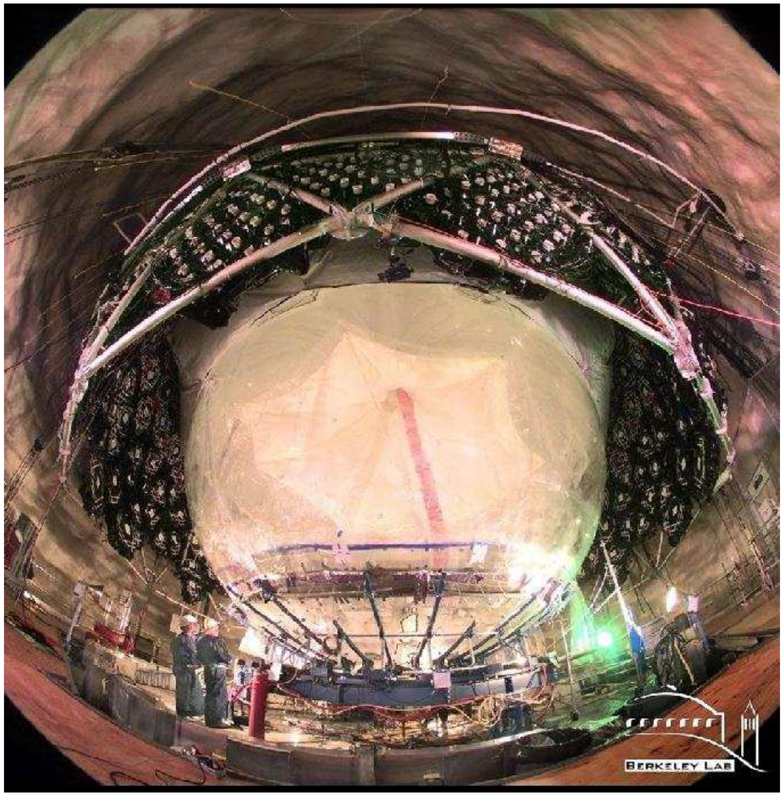




The detector

- SNO uses 1 kton heavy water + 1.7 kton water. Cherenkov light gathered by 9456 PMTs mounted on 17.8 m geodesic sphere.
- SNO located at a depth of 2092 meters under a flat overburden of 6010 mwe
  ➪ cosmic muons ~ 80 events/day





SNO timeline

Phase I (D_2O):
Nov'99 – May 01

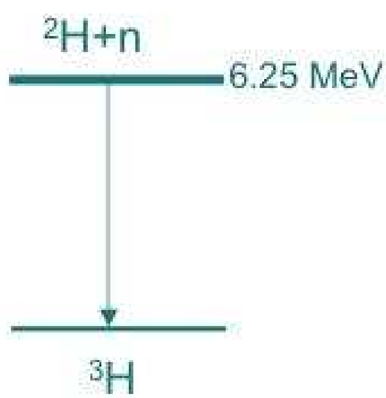
n captures on
$^2H(n,\gamma)^3H$
$\sigma = 0.0005$ b
Observe 6.25 MeV γ
PMT array readout

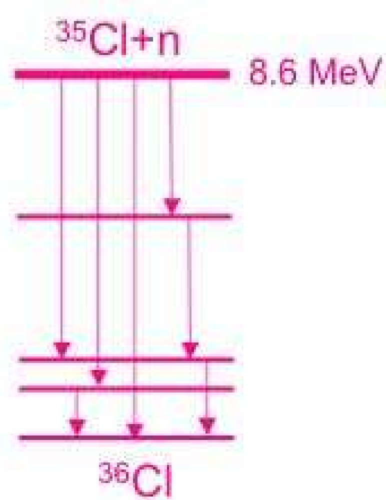
Phase II (salt):
Jul'01 – Sep'03

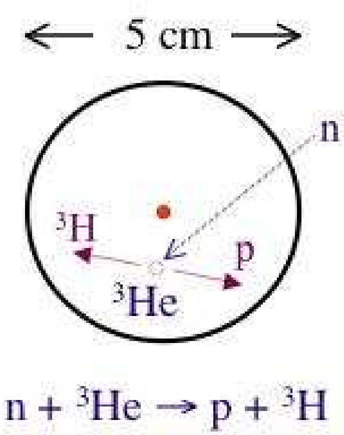
2t NaCl, n captures
on $^{35}Cl(n,\gamma)^{36}Cl$
$\sigma = 44$ b
Observe multiple γs
PMT array readout

Phase III (^{3}He):
current – Dec'06

40 proportionnal
counters
$^3He(n,p)^3H$
$\sigma = 5330$ b
Observe p and ^{3}H
PC independent
readout

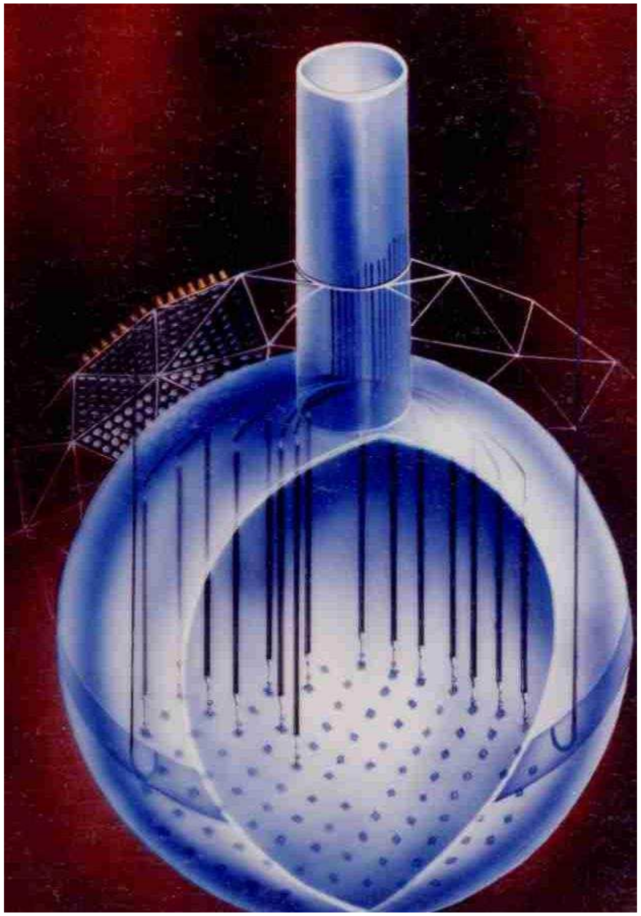


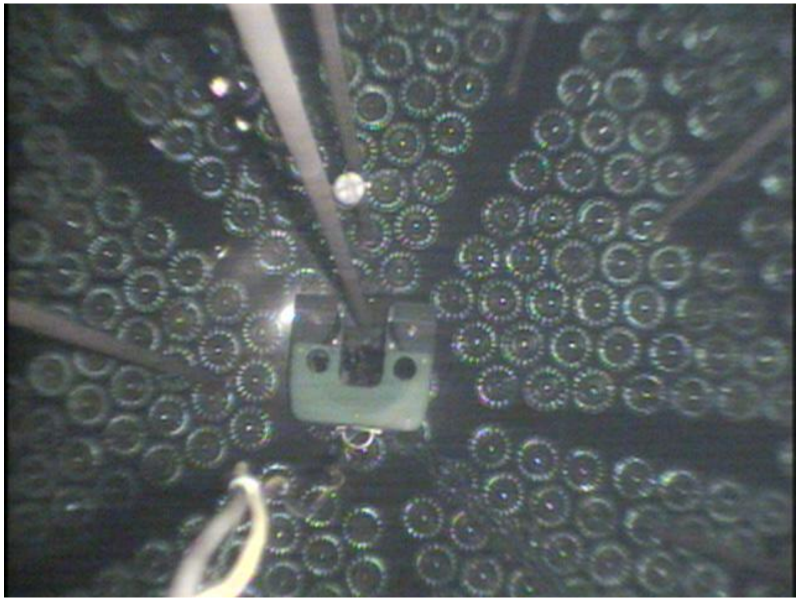




Phase III

Independent measurement of the neutrons with ^{3}He proportional counters, NCDs, array of 40 strings about 9m long each. Reaching end of commissioning period.





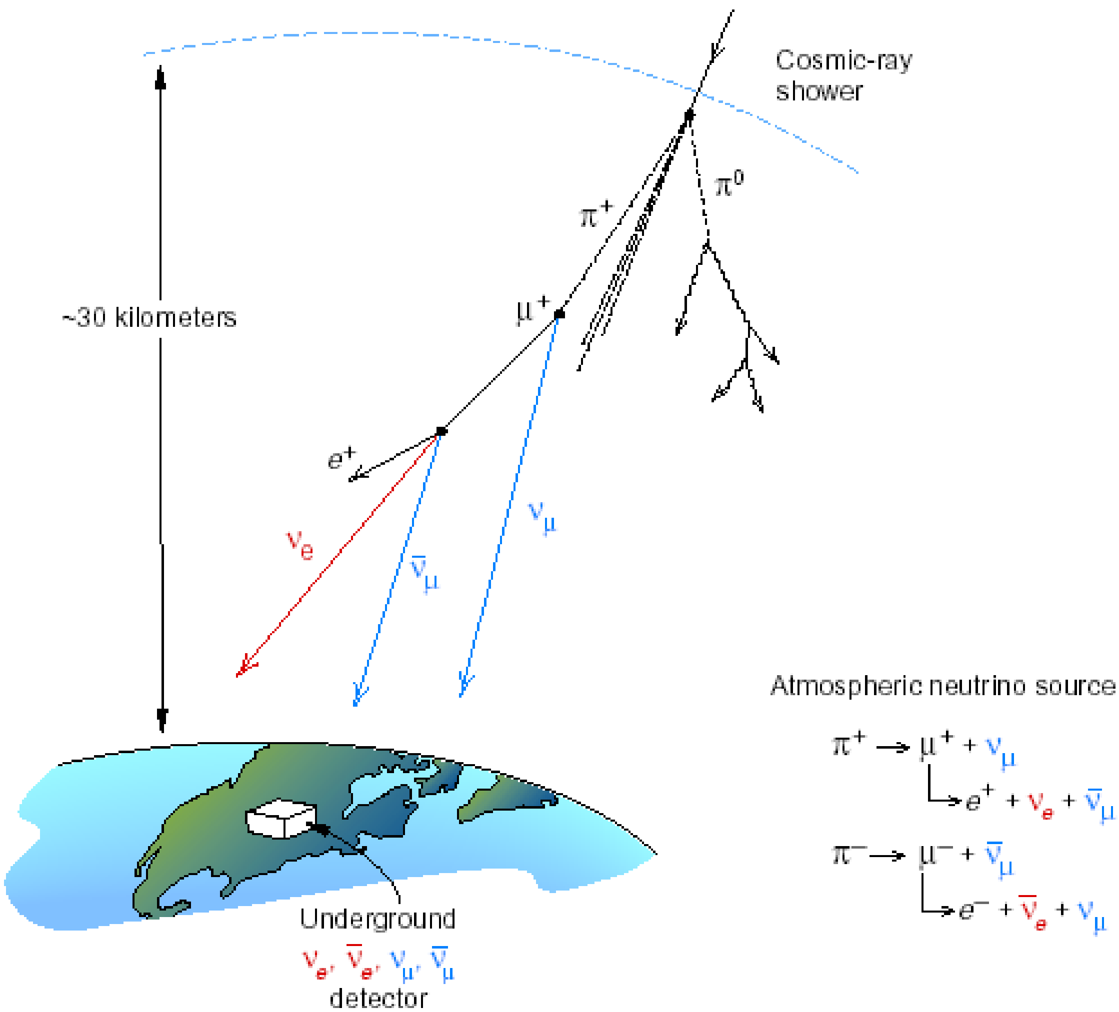
Is that all?

☞ What about atmospheric neutrinos in SNO?

The atmospheric ν anomaly in a nutshell

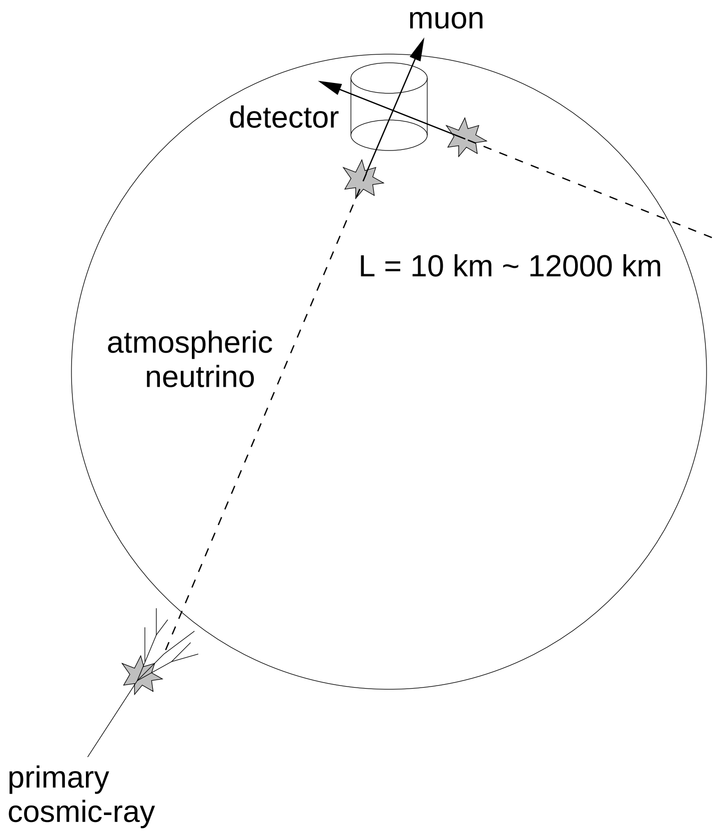
Atmospheric neutrinos are produced in the interactions of primary cosmic rays in the atmosphere. They penetrate the Earth arriving almost isotropically at the detector. The most accurately predicted feature of the atmospheric neutrinos is the ratio of the muon neutrino to the electron neutrino flux ($\pm 5\%$)

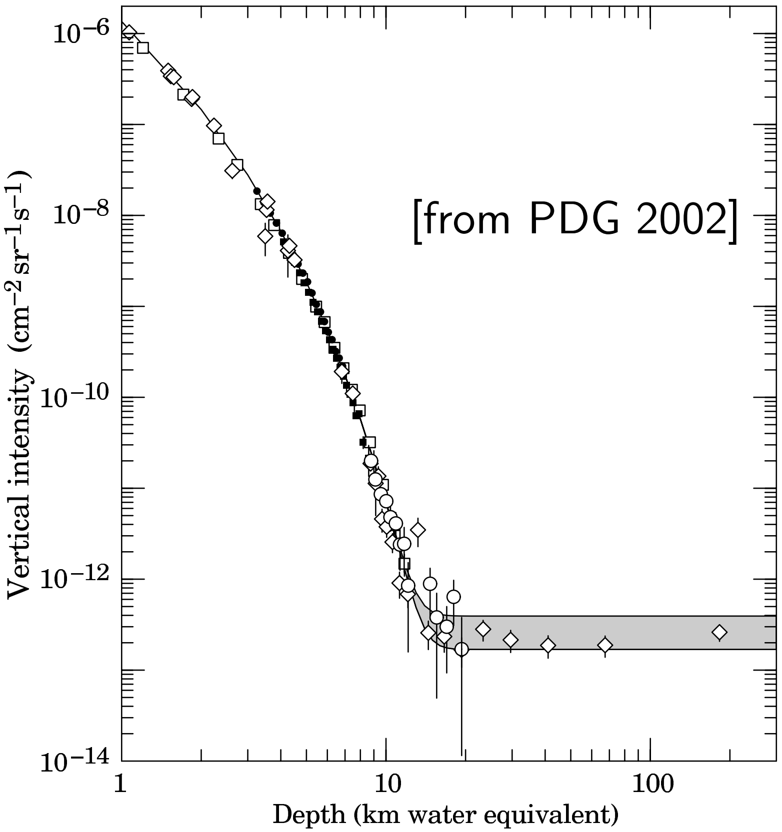
$$R = \frac{\nu_e + \bar{\nu_e}}{\nu_\mu + \bar{\nu_\mu}}$$



Two kinds of muons

The deeper you are, the less cosmic muons you will see...





☞ But... some neutrinos from cosmic showers will eventually undergo an interaction on their way through Earth... $\nu_\mu + N \longrightarrow \mu^\pm + N' + X$

The atmospheric ν anomaly

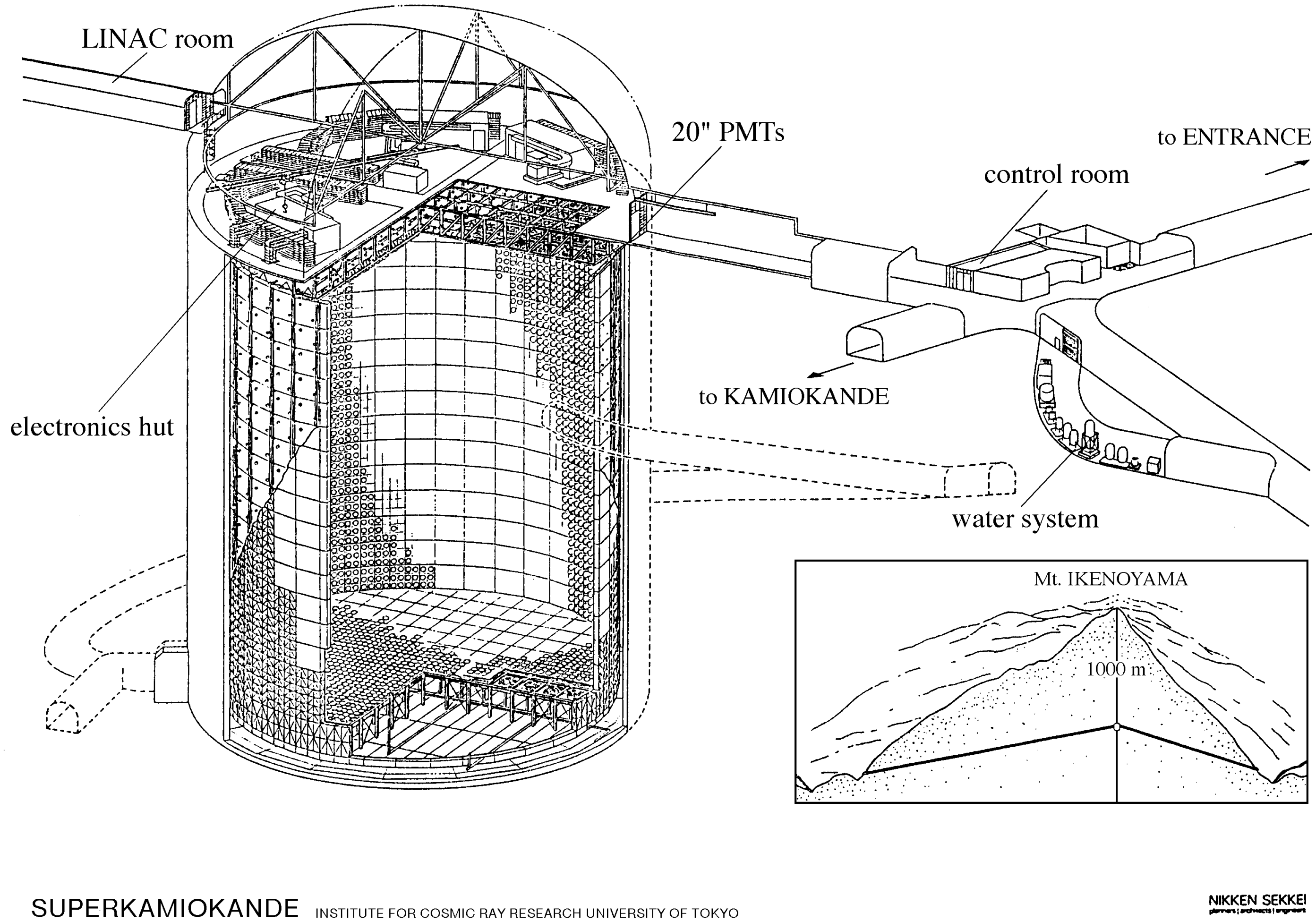
Better to measure deviation from

$$R = \frac{[N(\mu\text{-like})/N(e\text{-like})]_{\text{obs}}}{[N(\mu\text{-like})/N(e\text{-like})]_{\text{exp}}}$$

Experiment	R	Significance (kT·y)
Super-K (sub-GeV)	$0.638 \pm 0.017 \pm 0.050$	79
Super-K (multi-GeV)	$0.675^{+0.034}_{-0.032} \pm 0.080$	79
Soudan2	$0.69 \pm 0.10 \pm 0.06$	5.9
IMB	$0.54 \pm 0.05 \pm 0.11$	7.7
Kamiokande (sub-GeV)	$0.60^{+0.06}_{-0.05} \pm 0.05$	7.7
Kamiokande (multi-GeV)	$0.57^{+0.08}_{-0.07} \pm 0.07$	7.7
Frejus	$1.00 \pm 0.15 \pm 0.08$	2.0
Nusex	$0.96^{+0.32}_{-0.28} \pm 0.07$	0.74

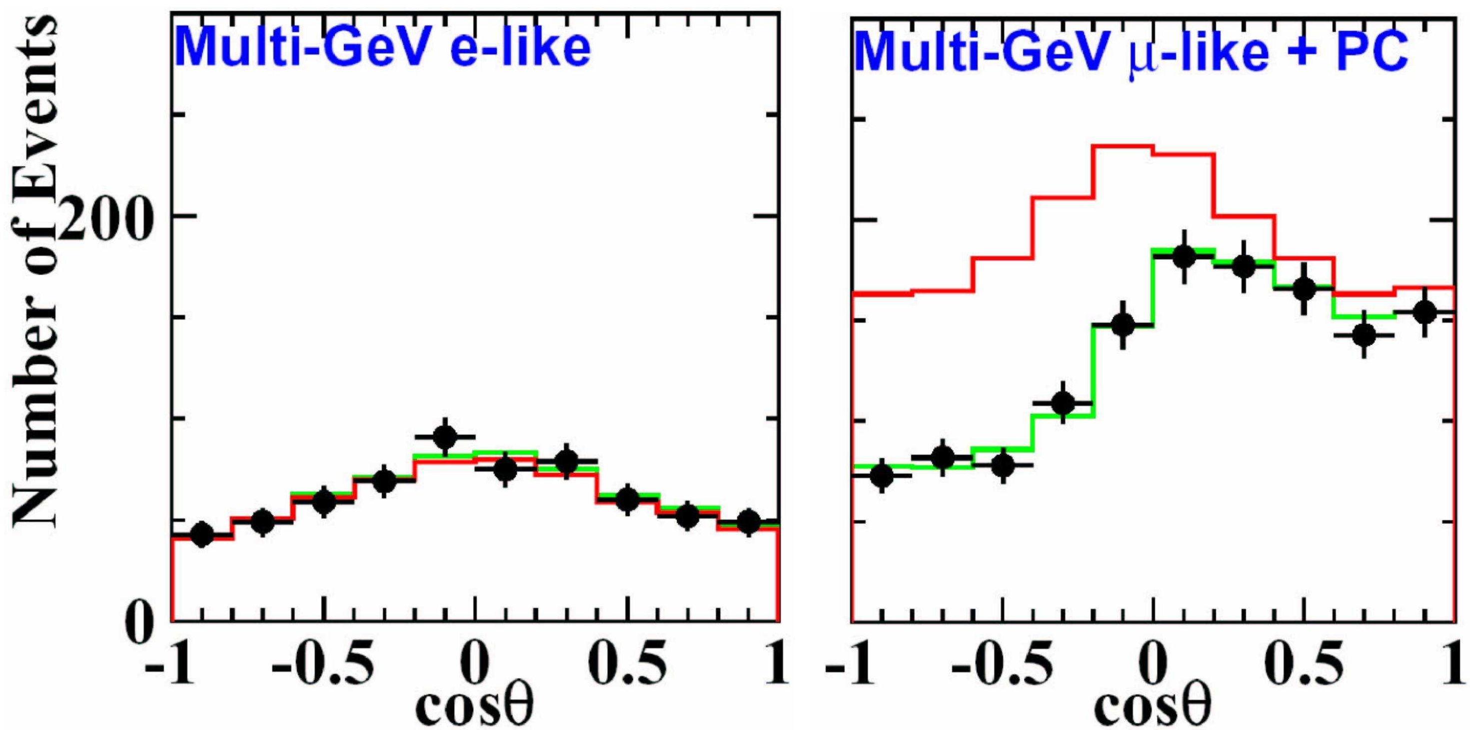
The Super-Kamiokande revolution (1998)

SuperK (WC, 50k tonnes H_2O) found evidence of atmospheric neutrino mixing, June'98, ν_μ disappearance. Kamioka mine, Japan (1000 m rock overburden).



The Super-Kamiokande revolution (1998)

SuperK (WC, 50k tonnes H_2O) found evidence of atmospheric neutrino mixing, June'98, ν_μ disappearance. Kamioka mine, Japan (1000 m rock overburden)



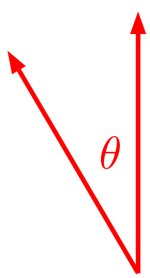
☞ Half of the ν_μ is lost!

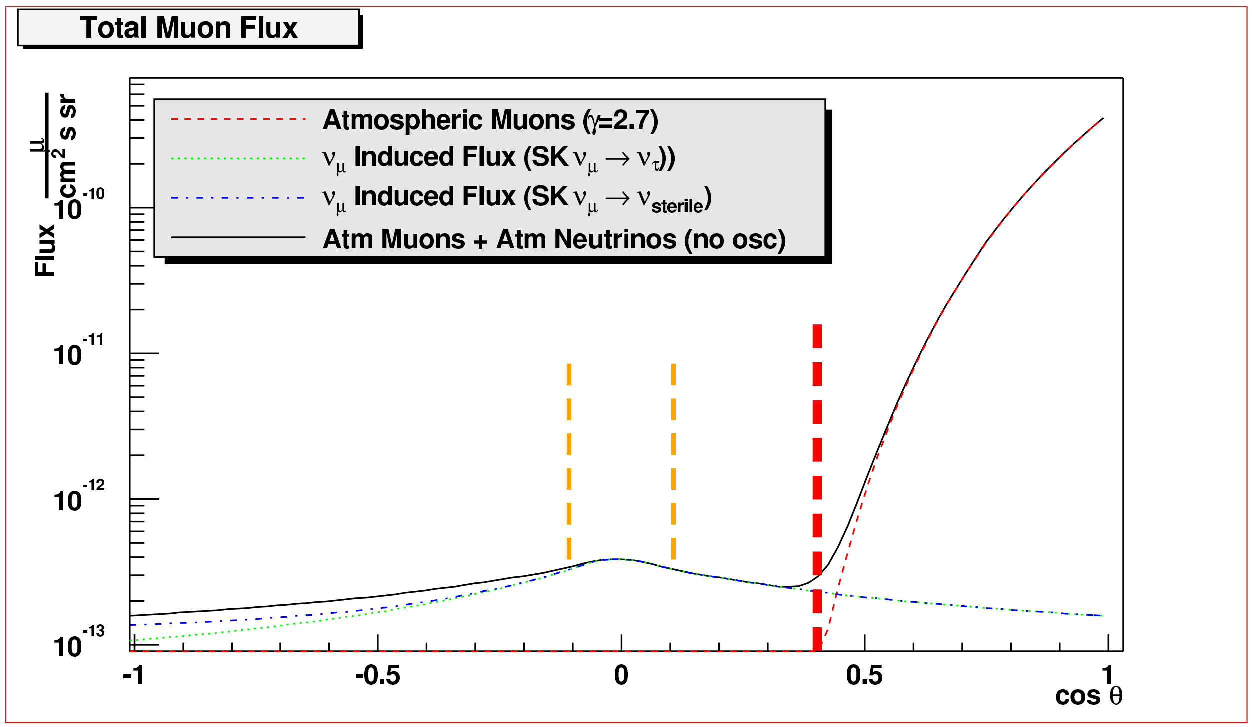
$$P(\ell \to \ell, x) = 1 - \sin^2 2\theta \times \sin^2(1.27 \cdot \Delta m^2 \cdot L[\text{km}]/E[\text{GeV}])$$

$$\Rightarrow (\sin^2 2\theta, \Delta m^2) = (1, 2.3 \times 10^{-3}[\text{eV}^2])$$

Atmospheric neutrinos in SNO 1/2

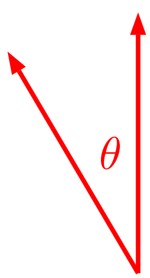
- SNO is of modest size ➪ cannot perform contained events analysis, e-like/μ-like ➪ zenith angle distribution of muons (up vs down)
- For zenith angles $\theta_{\text{zenith}} < 66^\circ$ $(\cos\theta > 0.4)$, muons from cosmic-rays
- For $\theta_{\text{zenith}} > 66^\circ$ ➪ muons generated in neutrino interactions in the rock

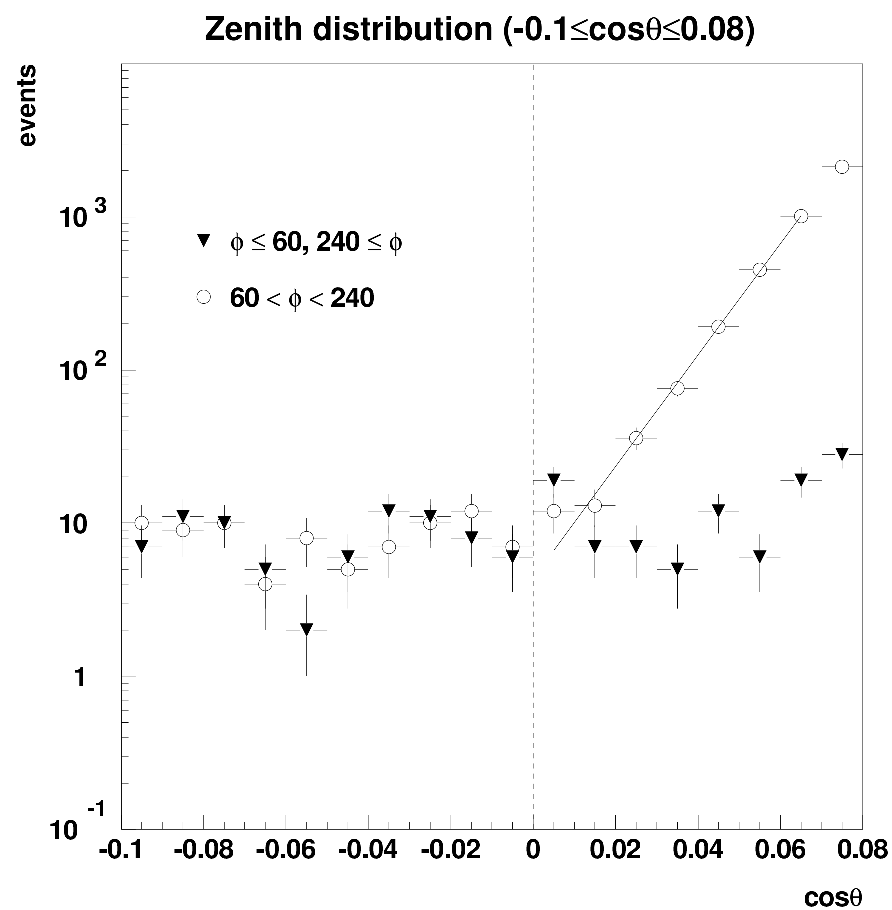




Atmospheric neutrinos in SNO 1/2

- SNO is of modest size ➪ cannot perform contained events analysis, e-like/μ-like ➪ zenith angle distribution of muons (up vs down)
- For zenith angles $\theta_{\text{zenith}} < 66^\circ$ $(\cos\theta > 0.4)$, muons from cosmic-rays
- For $\theta_{\text{zenith}} > 66^\circ$ ➪ muons generated in neutrino interactions in the rock

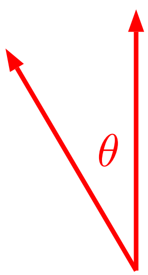


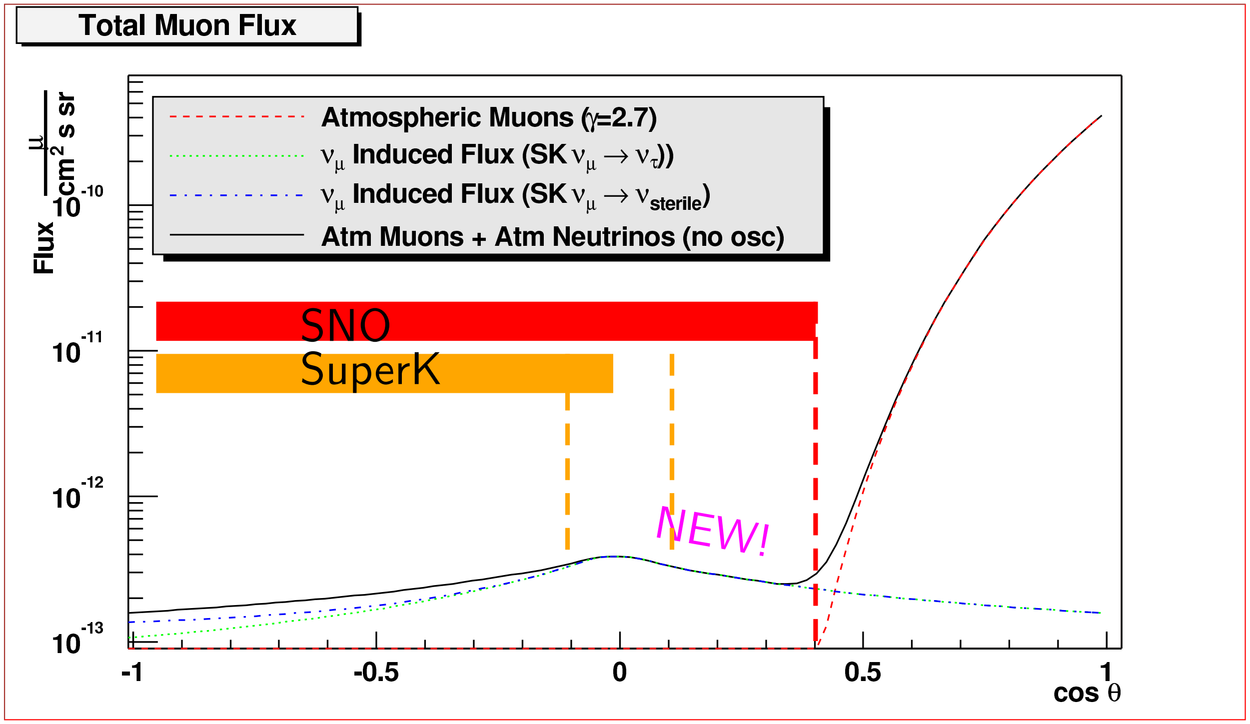


[M. Takahata, SuperK thesis]

Atmospheric neutrinos in SNO 1/2

- SNO is of modest size ➪ cannot perform contained events analysis, e-like/μ-like ➪ zenith angle distribution of muons (up vs down)
- For zenith angles $\theta_{\text{zenith}} < 66°$ $(\cos\theta > 0.4)$, muons from cosmic-rays
- For $\theta_{\text{zenith}} > 66°$ ➪ muons generated in neutrino interactions in the rock

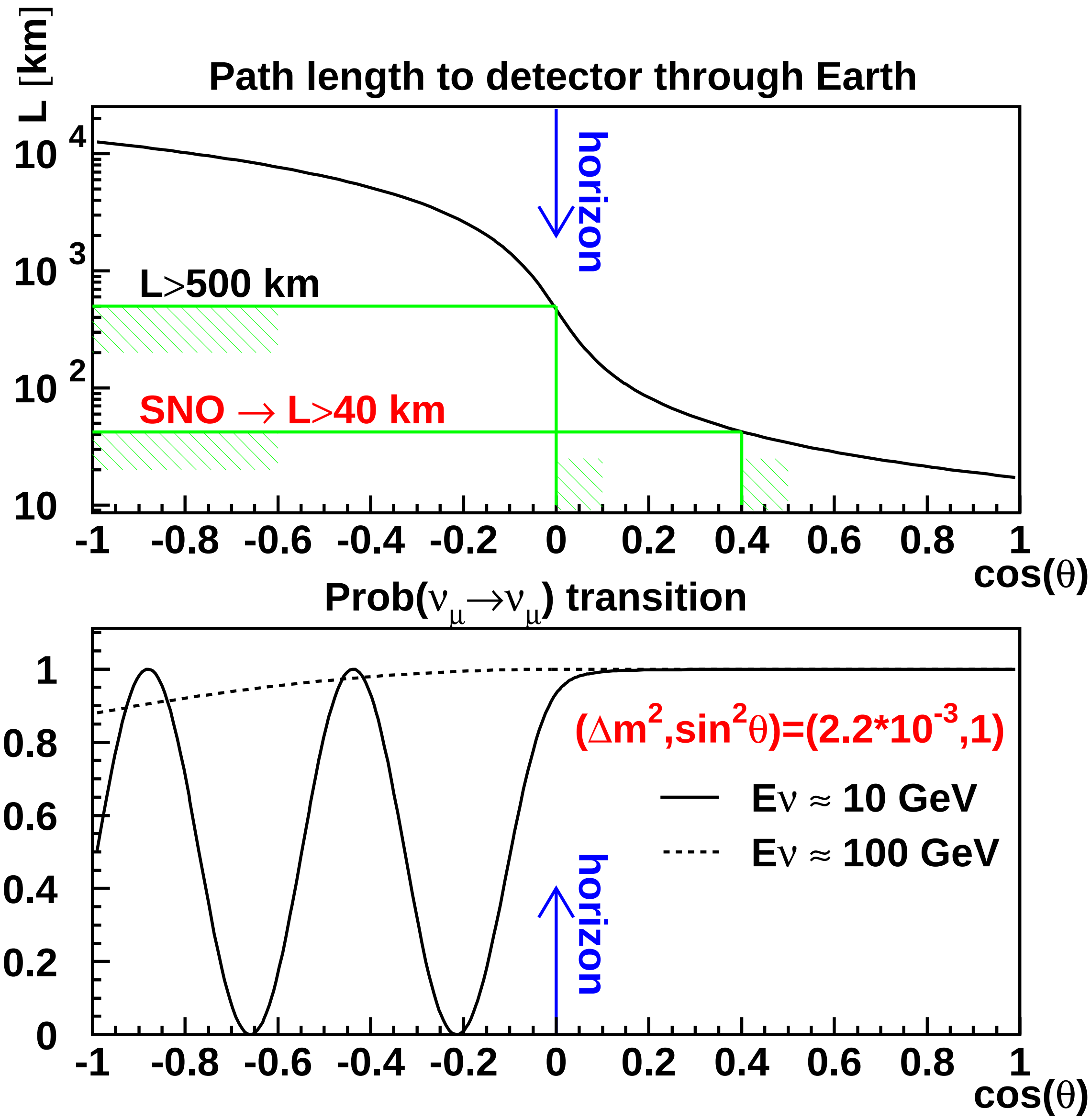




☞ Deep location permits direct measurement of absolute neutrino flux ➪ horizon is clear (no model-dependent shape correction)

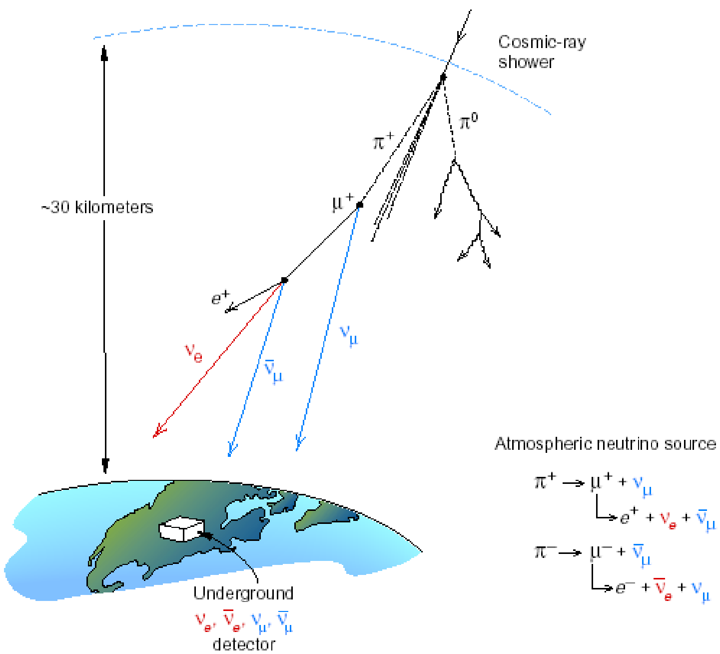
Atmospheric neutrinos in SNO 2/2

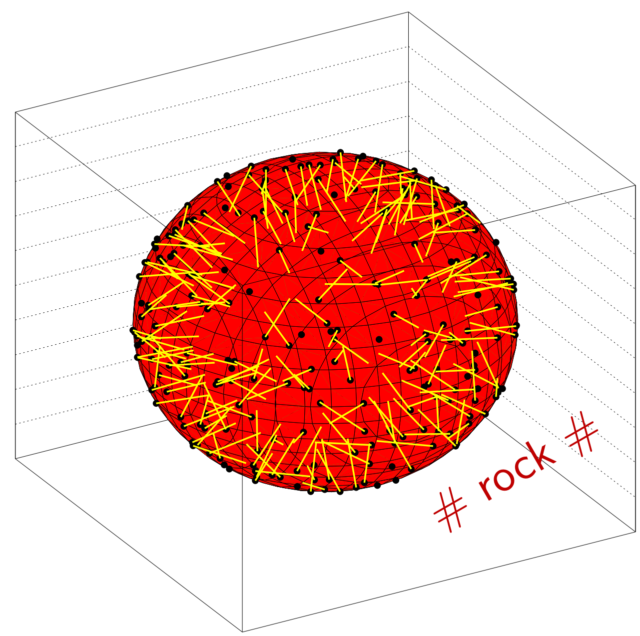
- By studying muon flux as $f(\theta_{\mathsf{zenith}})$ it is also possible to study neutrino oscillations
- Only events coming from below the horizon may oscillate
  ➪ distortion in angular distribution shape



$$P(\ell \to \ell, x) = 1 - \sin^2 2\theta \times \sin^2(1.27 \cdot \Delta m^2 \cdot L[\mathrm{km}]/E[\mathrm{GeV}])$$

- Simulation of neutrino-induced upward-going muons using `Nuance` (package for simulating neutrino propagation and interactions) according to Bartol flux up to detector's edge
- Interfaced with collaboration software for detailed simulation



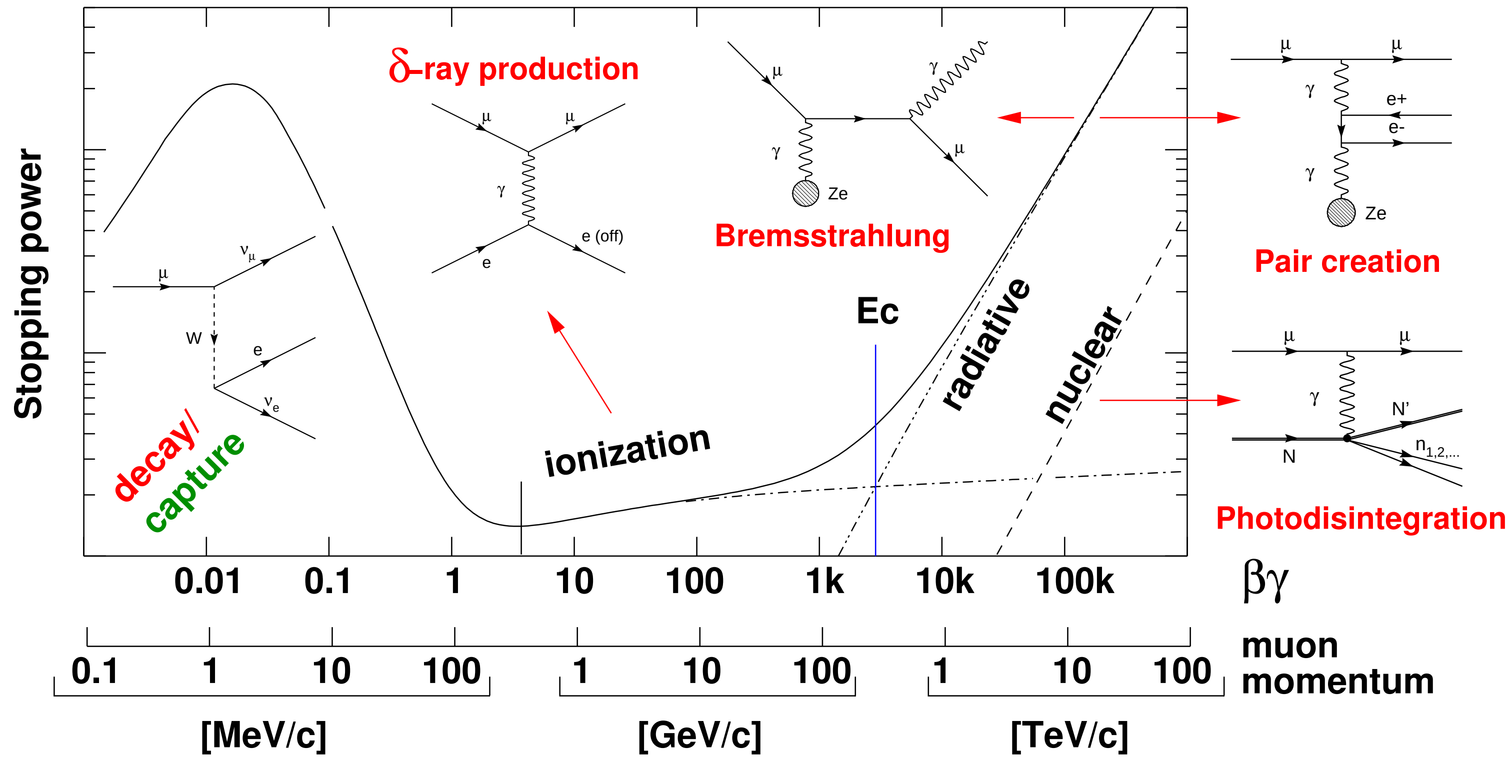


Nuance to Snoman kinl0 v3

☞ Rate = (Flux) × (Cross section)

Muon simulation 2/2

- Simulation of neutrino-induced upward-going muons using `Nuance` (package for simulating neutrino propagation and interactions) according to Bartol flux up to detector's edge
- Interfaced with collaboration software for detailed simulation

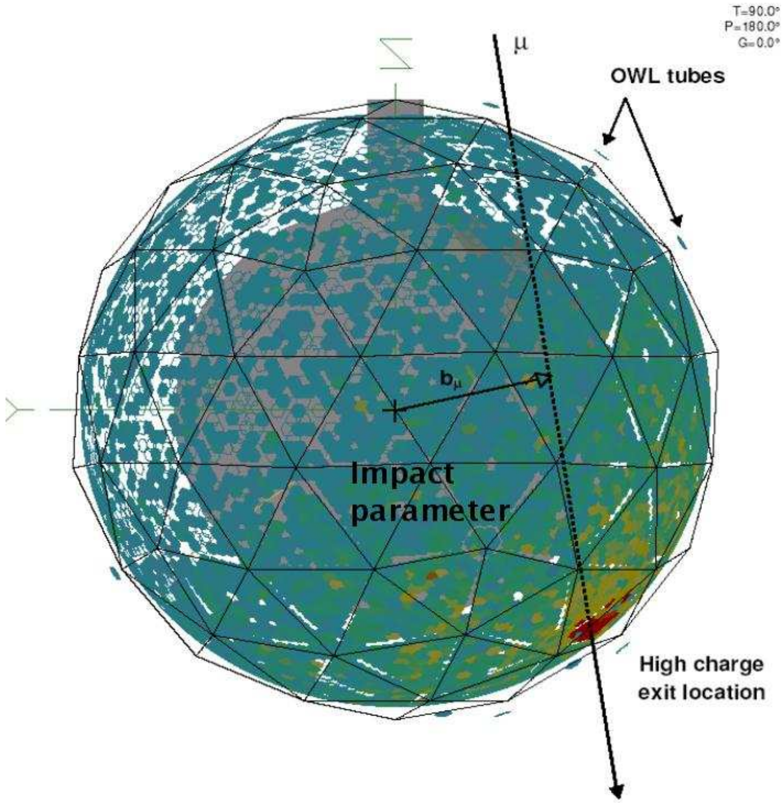


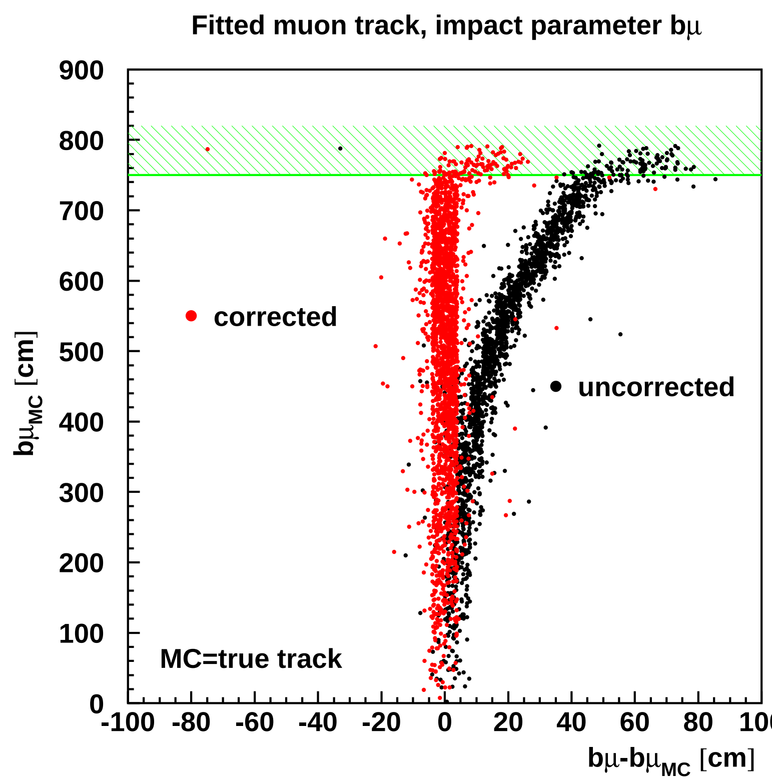
- N.B.: given the size of SNO, there is no contained muon interaction

Muon measurement

Muon track reconstruction proceeds in 2 steps: (1) high charge cluster to locate exit point / (2) use of PMTs timing to reconstruct track direction

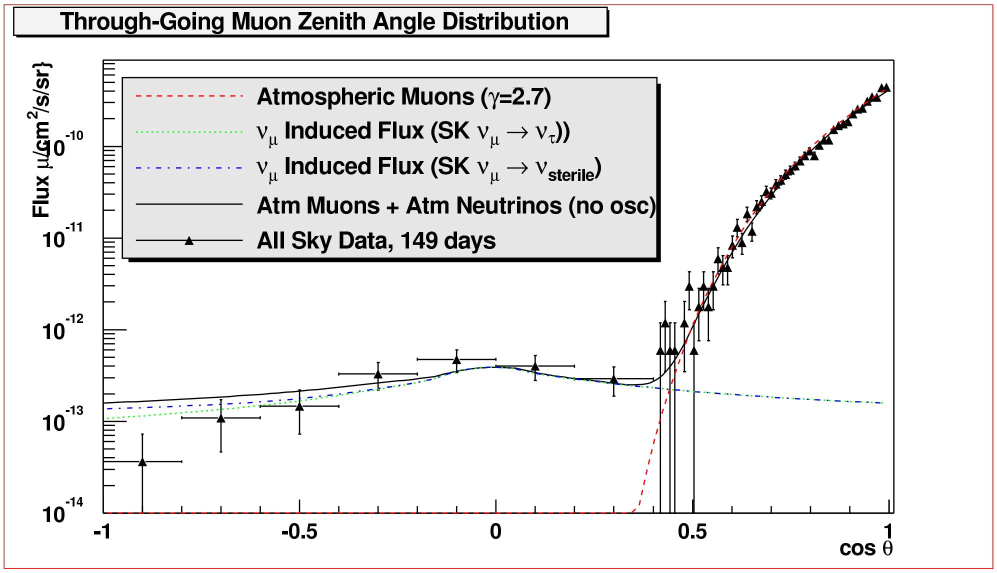
- typical error on impact parameter $\sigma_{b_\mu} \simeq 15$ cm
- typical error on direction $\sigma_\theta \simeq 1.5^\circ$
- systematic effects such as radial bias are corrected as f(impact parameter)



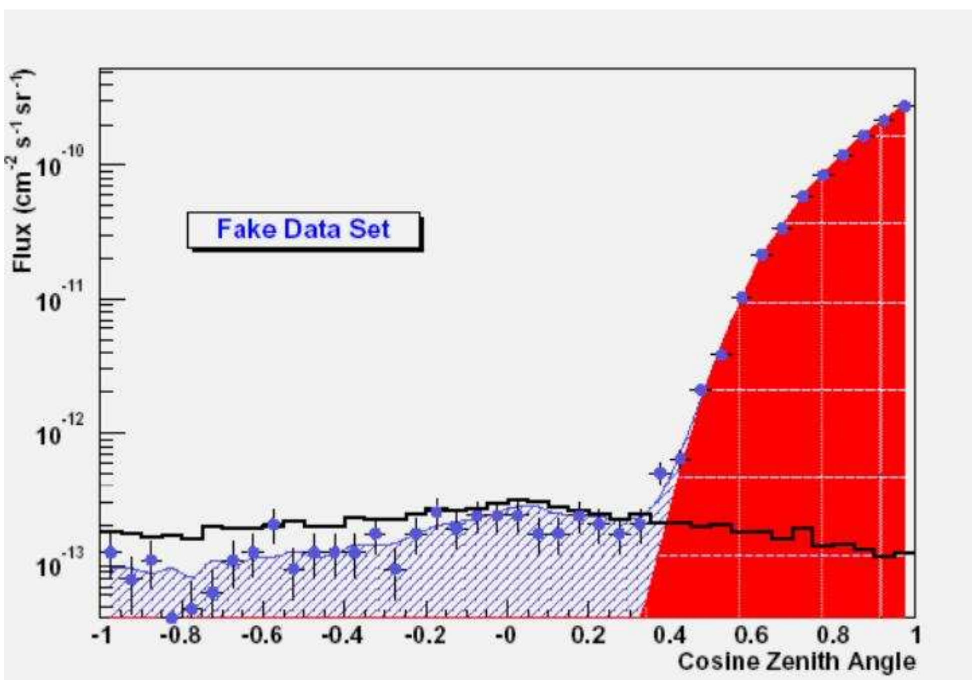


☞ Reconstruction efficiency $\epsilon \simeq 1$ for energies $E_\mu \gtrsim 4$ GeV (stopping range $\sim$ detector size) and for $R < 7.5$ m ($R_{\text{MAX}} = 8.9$ m)

Preliminary analysis with 150 days of data carried out in 2001 (courtesy of N. Tagg)



Prospect at SNO with 730 days of data ☞ simulated data set



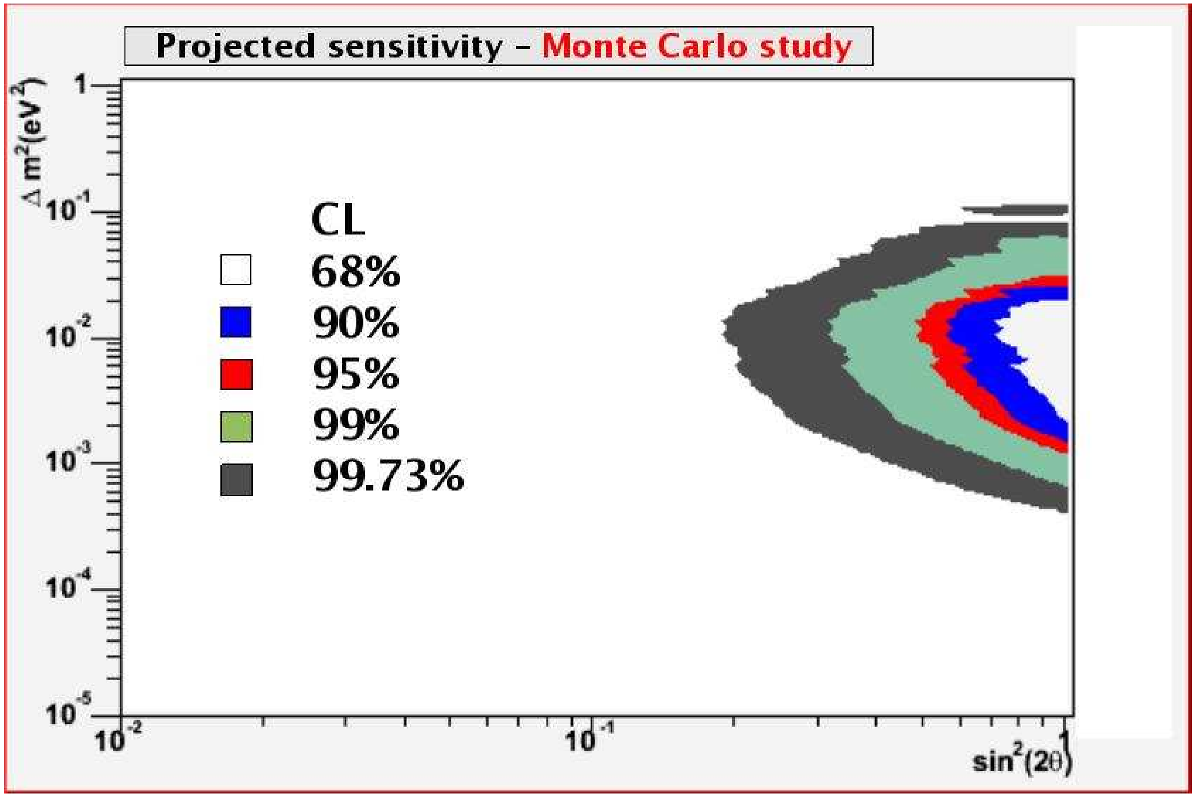
- data point $(\Delta m^2, \sin^2\theta) = (5\times 10^{-3}\text{eV}^2, 1)$

☞ stop/thru analysis under investigation

Projected sensitivity 2/2

Projected sensitivity to atmospheric neutrino-oscillation parameters at SNO

- ... with 730 days of data (as of Winter 2003)
- ... with flux constraint
- ... data point $(\Delta m^2, \sin^2\theta) = (5 \times 10^{-3}\text{eV}^2, 1)$
- ... MC study, statistical only



$$P(\ell \to \ell, x) = 1 - \sin^2 2\theta \times \sin^2(1.27 \cdot \Delta m^2 \cdot L[\text{km}]/E[\text{GeV}])$$

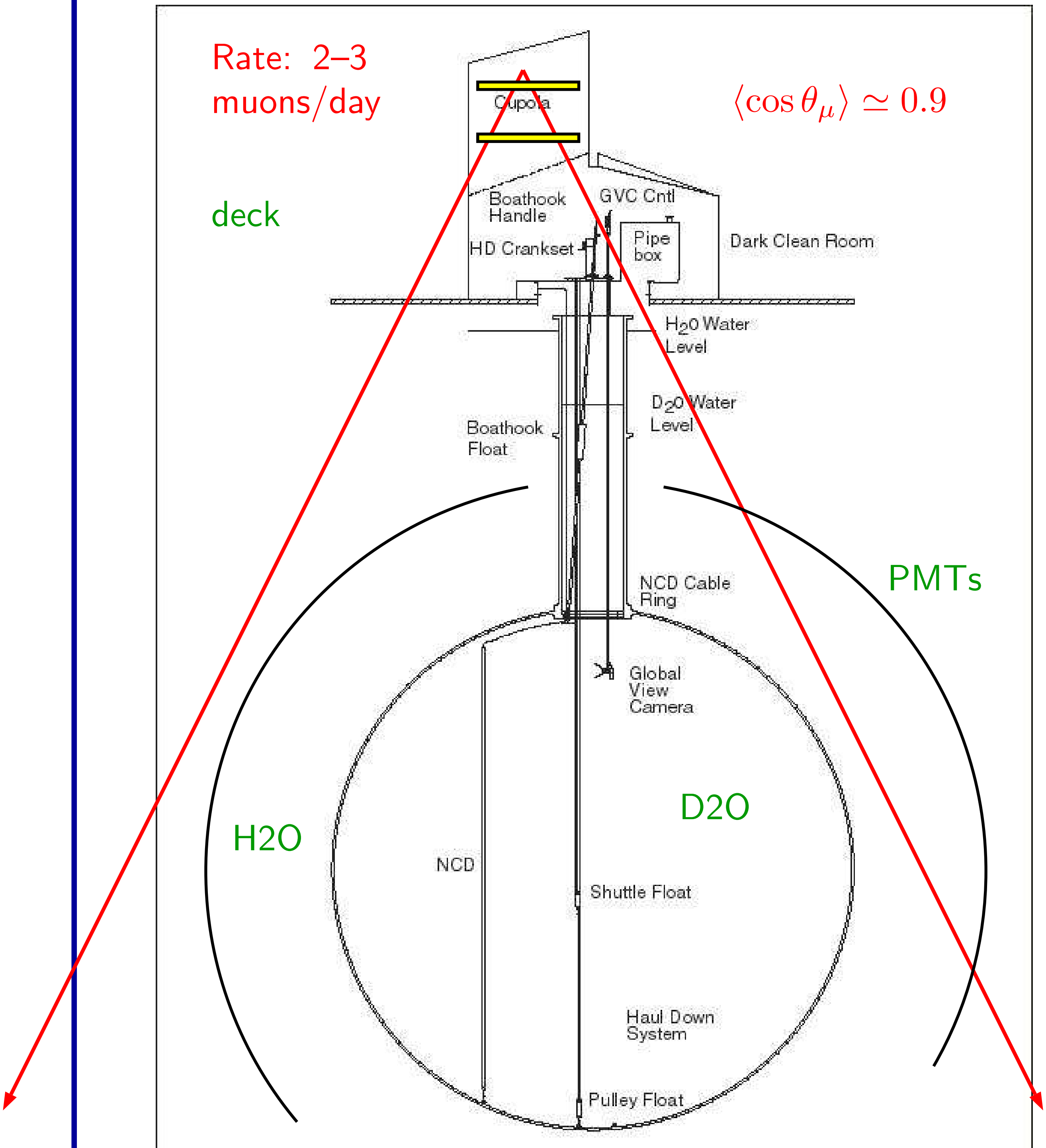
Possible muon calibration

☞ Analysis in progress...

- Systematics (in track reconstruction) have strong impact on sensitivity studies
- Statistics really matter ➪ improved fitter acceptance at large impact parameters is welcome
- Simulation and reconstruction algorithm to be tuned on independent data

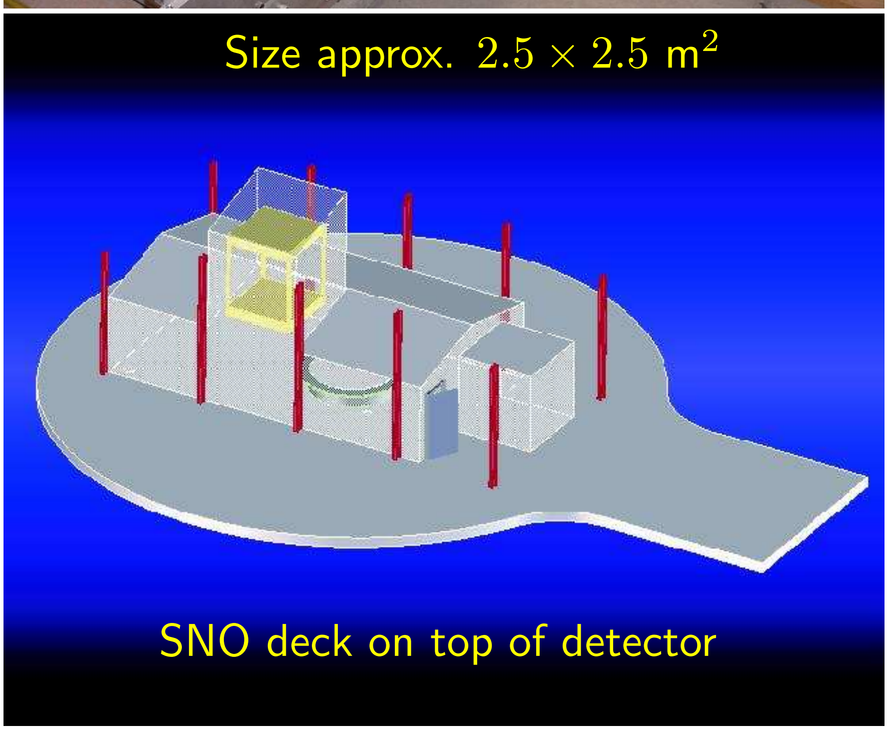
☞ Study feasibility of standalone muon tracker (with application at SNO) in progress

Location & coverage



Muon tracker project

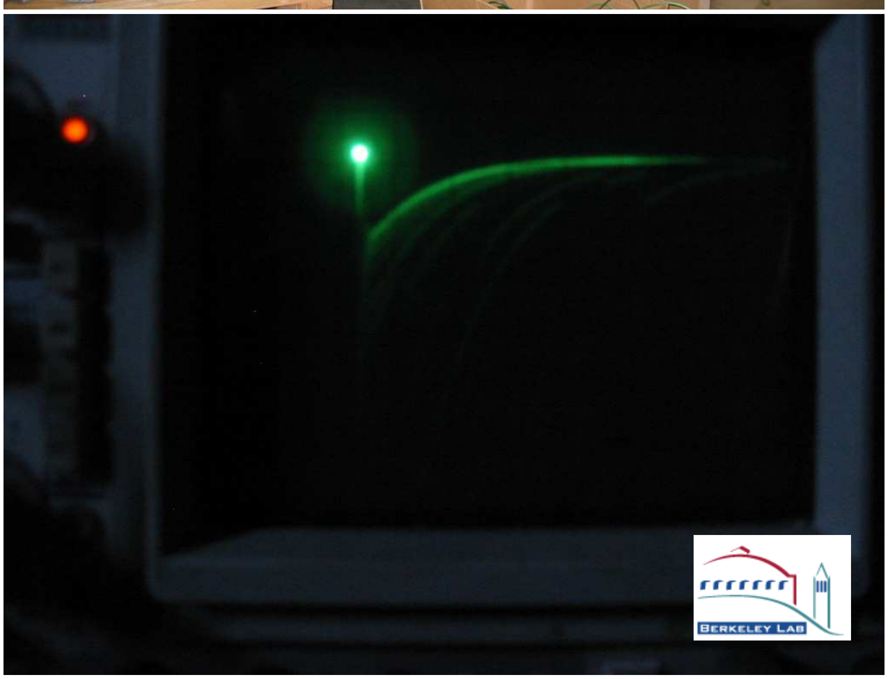
Recycling chambers used for HEP test beams (FNAL/IUCF/JLab)



Muon tracker project

Muon tracker project

Some engineering work required for SNO needs: scintillator pads for trigger, support structure. Getting ready at building 88...



Conclusion & perspectives

- SNO and MINOS are the only experiments currently able to perform atmospheric neutrino studies (SuperK in reconstruction)
- Atmospheric analysis in SNO fully on track: advertised/recognized at Neutrino 2004, DPF 2004
- Lots of work, small group...
- Paper for next year!

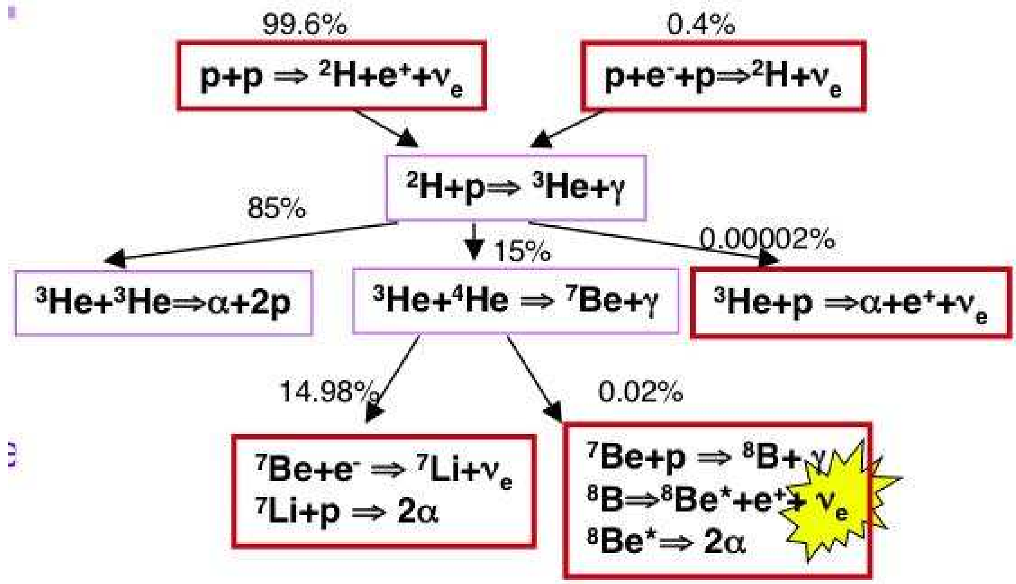
Spare slides

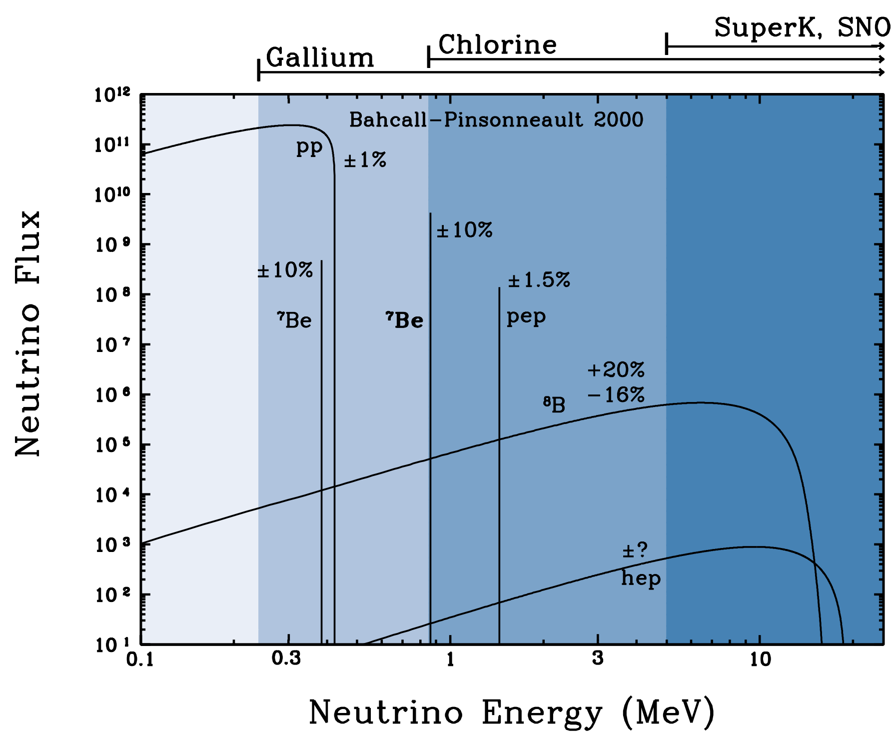
☞ STOP! Spare slides next...

Spare: Solar neutrinos

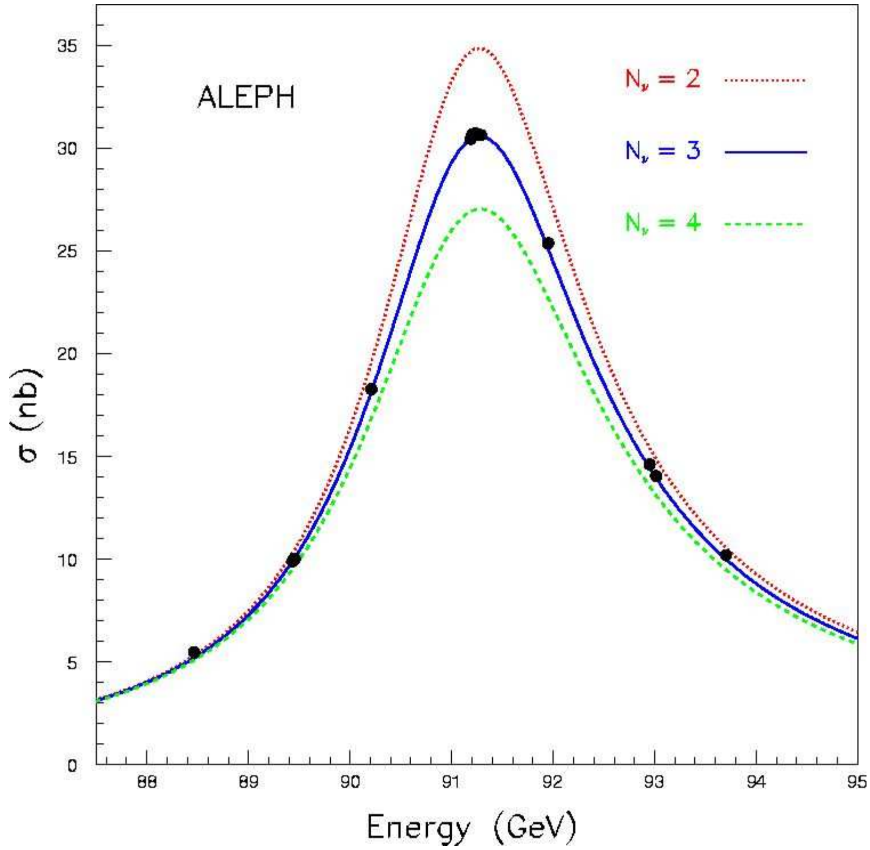
The Sun creates its energy via nuclear fusion:

$4p \longrightarrow {}^4\text{He} + 2e^+ + 2\nu_e$

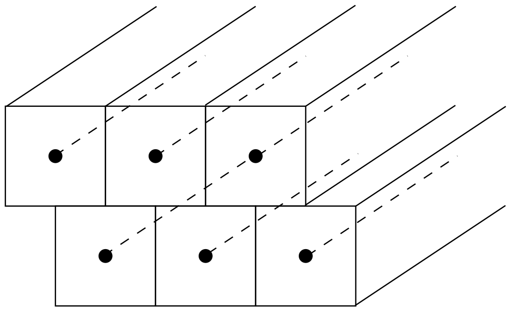




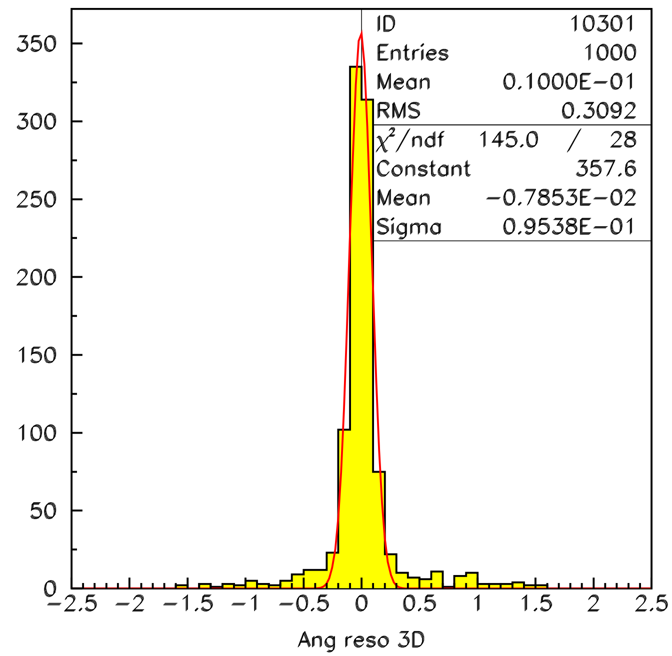
As measured by the Aleph experiment



Simulation based study of the configuration of the muon tracker.

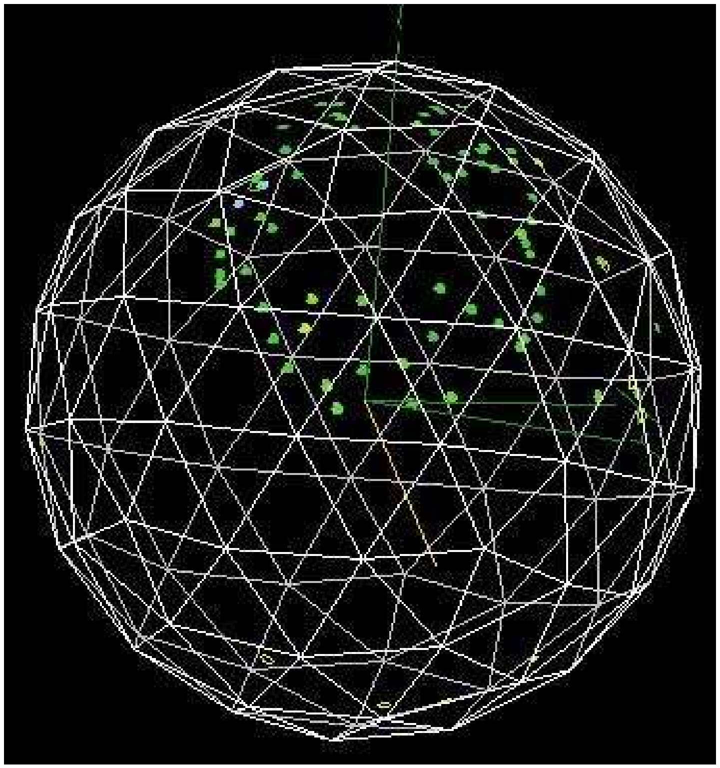


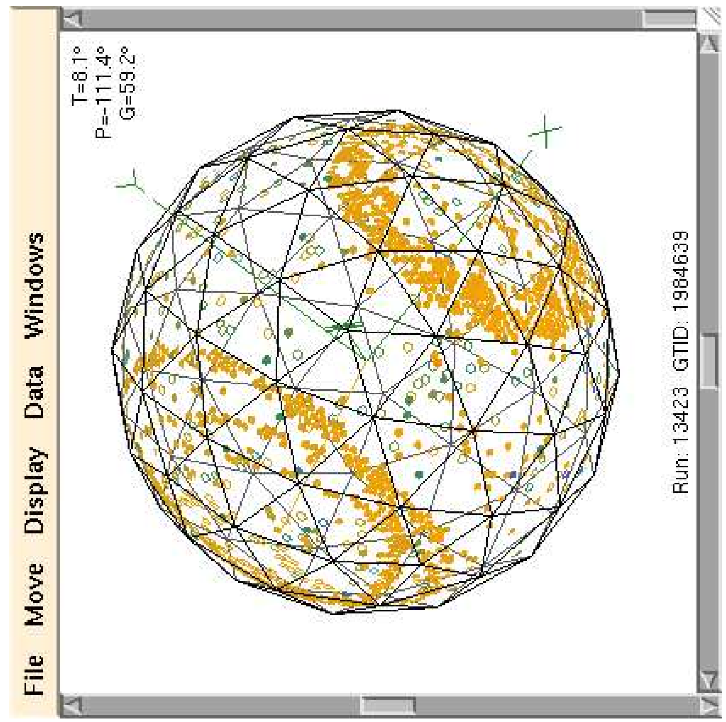
Cell size: 7.5 cm x 7.5 cm
Longitudinal resolution: 5 mm
Transverse resolution: 500 microns
Stations: 2, 2 layers each, 2 m apart



Spare: The lord of the (electron) rings

We measure Cerenkov rings produced by electrons (solar analysis). PMTs timing information allows to reconstruct interaction vertex.

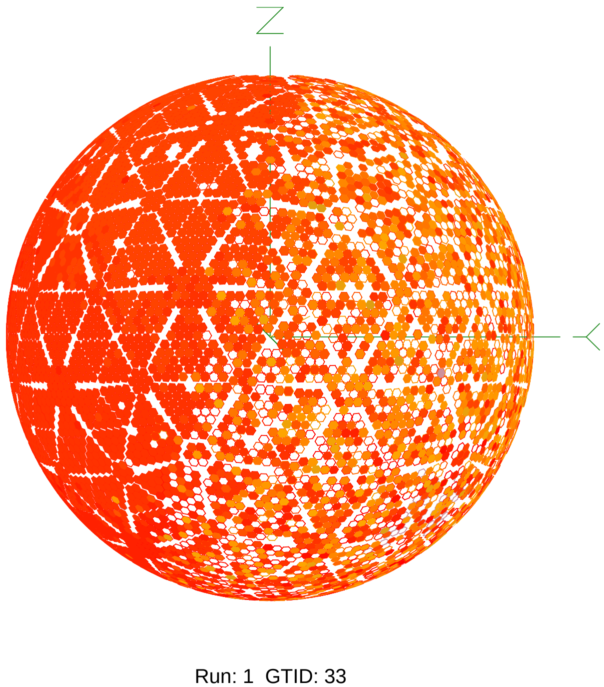




Spare: The lord of the (muon) rings

We measure Cerenkov light produced by muons too (atmospheric analysis). PMTs timing information allows to reconstruct the direction of the traversing muon. Very few muon stop in the detector (range is 18 m for $E_\mu = 4$ GeV).

$E_\mu \simeq 150$ GeV



$E_\mu \simeq 2$ GeV